



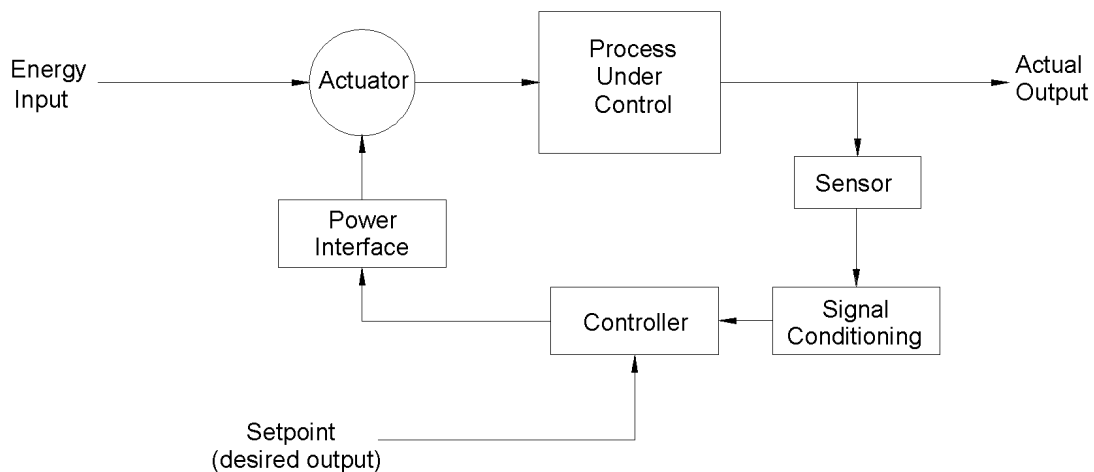
Experiment #5: Closed-Loop Control

An open-loop control system can deliver a desired output if the process is well understood and all conditions affecting the process are constant. However, Experiment #4 showed us that an open-loop control system couldn't guarantee the desired output from a process that was subject to even mild disturbances. There is no mechanism in an open-loop system to

react when disturbances affect the output. Although you were able to find a drive setting that would yield the desired temperature in Experiment #4, when the fan was moved closer or further from the heater, the fixed setting was no longer valid. Closed-loop control provides automatic adjustment of a process by collecting and evaluating data and responding to it accordingly. A typical block diagram of an automatic control system is depicted in Figure 5.1.

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Figure 5.1: Closed-Loop Control



In this diagram, an appropriate sensor is measuring the Actual Output. The signal-conditioning block takes the raw output of the sensor and converts it into data for the Controller block. The Setpoint is an input to the Controller block that represents the desired output of the process. The controller evaluates the two pieces of data. Based on this evaluation, the controller initiates action on the Power Interface. This block provides the signal conditioning at the controller's output. Experiment #3 discussed several methods of driving power interface circuits. The Power Interface has the ability to control the Actuator. This may be a relay, a solenoid valve, a motor drive, etc. The action taken by the Actuator is appropriate to drive the Actual Output toward the desired value.

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As you can see, this control scenario forms a loop, a closed-loop. Furthermore, since it is the process's output that is being measured, and its value determines actuator settings, it is a feedback closed-loop system. The input changes the process output → the output is monitored for evaluation → the evaluation changes the input → that changes the process output, etc., etc.

The type of reaction that takes place upon evaluation of the input defines the process-control mode. There are five common control modes. They are on-off, on-off with differential gap, proportional, integral, and derivative. The fundamental characteristic that distinguishes each control mode is listed below in Table 5.1.

Table 5.1: Five Common Control Modes

Process Control Mode	Evaluation	Action
On-off	Is the variable above or below a specific desired value?	Drive the output fully ON or fully OFF.
On-off with differential gap	Is the variable above or below a range defined by an upper and lower limit?	Output is turned fully ON and fully OFF to drive the measured value through a range.
Proportional	How far is the measured variable away from the desired value?	Take a degree of action relative to the magnitude of the error.
Integral	Does the error still persist?	Continue taking more forceful action for the duration the error exists.
Derivative	How fast is the error occurring?	Take action based on the rate at which the error is occurring.

This exercise will focus on converting the open-loop temperature control system of Experiment #4 into an on-off closed-loop system. Our system will show advantages and disadvantages to this method of control. The characteristics of the system being controlled determines how suitable a particular control mode will be. Experiment #6 will use the same circuitry to overview and apply proportional, integral, and derivative control modes. Leave the circuit constructed after completing this step.

Figure 5.2 is a schematic of the circuitry necessary for the next two exercises. As you see, this is identical to Experiment #4. The 35-mm film canister provides the environment we wish to control. The heater drive provides full power for developing heat in the resistor. The LED is also driven by Pin 8. Remember that the LED is driven by the +5-V_{dd} supply, and the heater is driven by the +9-volt unregulated line supply. The LM34 sensor will provide temperature data. In closed-loop control, we will monitor the temperature and use it to determine control levels. The fan's air currents will act as a disturbance to the process.

Figure 5.2: Closed-Loop Control Circuitry

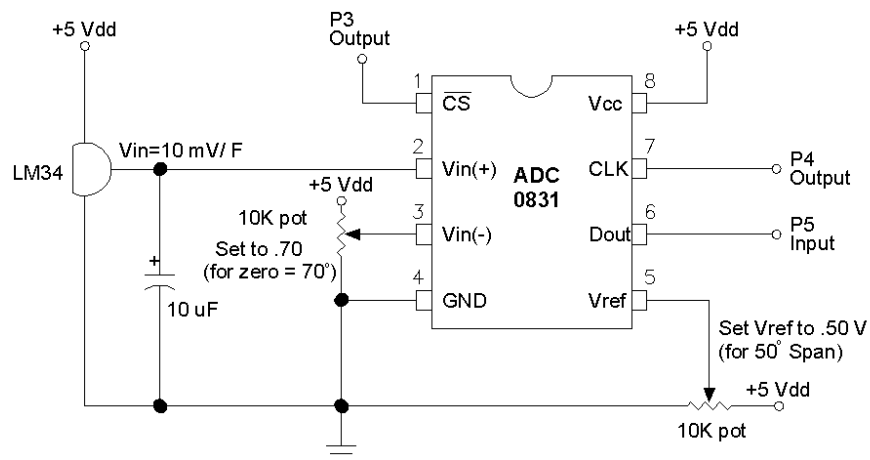
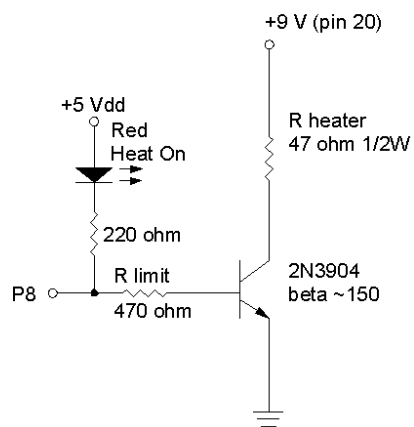
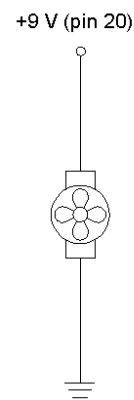


Figure 5.2a: LM34 to ADC0831 Serial A-to-D

Figure 5.2b: BASIC Stamp
Driving the Heater with LED IndicatorFigure 5.2c: Brushless Fan -
Directly Connected

Experiment #5: Closed-Loop Control

If the circuit isn't already on your board, carefully construct it. Use space on the small Board of Education efficiently to allow for the circuitry. Take your time, plan your layout, and be careful not to inadvertently short any wires. Refer back to Experiment #4 for details on the film canister construction, the operation of the LM34, and the use of the ADC0831 analog-to-digital converter.

Double-check the Zero and Span voltages of the ADC0831. Use your voltmeter to set the Zero voltage ($V_{in(-)}$) to .7 and the Span (V_{ref}) to .5 volts. This will establish a full-scale temperature measurement range from 70 to 120 degrees F.



Exercises

Exercise #1: Establishing Closed-Loop Control

Let's assume it is our objective to maintain temperature within the canister at $101.50^{\circ}\text{F} \pm 1$ degree. This would be representative of the requirements of an incubator used for hatching eggs. Maintaining the eggs at the setpoint temperature of 101.5°F is perfect, but the temperature could go up to 102.50 or down to 100.50 without damage to the embryos. Although it may be hard to imagine an incubator when you look at your film canister, the BASIC Stamp would be well suited as the controller in a large commercial hatchery incubator.

To maintain temperature at the desired value seems like a pretty "common sense" task. That is, simply measure temperature; if it is above the setpoint, turn the heater OFF; and, if it is below, turn the heater ON. The simplest kind of control mode is on-off control. There are drawbacks to this control mode, however. During the following exercise, you will establish on-off control of your model incubator. Pay close attention to the characteristics exhibited by your model. These characteristics would also apply to real control applications.

Procedure

Programming for this application requires data acquisition, evaluation, and control action. Our display routine will also include storing and displaying the minimum and maximum overshoot in the process.

The structure and much of the content of Program 4.1 may be used to acquire and calculate our measurement. Instead of turning the heater on continually, a new subroutine will be added to evaluate and control it. Evaluation will be based on a **setpoint** variable. Refer to Program 5.1 following.

```

'Program 5.1: Simple ON/OFF Control with the StampPlot Interface

'This program establishes simple ON/OFF control of the model incubator.
'Program I/O is based on the circuitry of Figure 5.2.
'Zero and Span voltages: Digital 0 = Vin(-) = .70V and Span = Vref = .50V.

'Configure Plot
Pause 500                                'Allow buffer to clear
DEBUG "!RSET",CR                         'Reset plot to clear data
DEBUG "!TITL Simple ON/OFF Control",CR   'Caption form
DEBUG "!PNTS 60000",CR                   '2000 sample data points
DEBUG "!TMAX 300",CR                     'Max 300 seconds
DEBUG "!SPAN 70,120",CR                  '70-120 degrees
DEBUG "!AMUL .1",CR                      'Multiply data by .1
DEBUG "!DELD",CR                         'Delete Data File
DEBUG "!CLMM",CR                         'Clear Min/Max
DEBUG "!CLRM",CR                         'Clear Messages
DEBUG "!USRS ",CR                        'Clear User status bar
DEBUG "!SAVD ON",CR                      'Save Data
DEBUG "!TSMP ON",CR                      'Time Stamp On
DEBUG "!SHFT ON",CR                      'Enable plot shift
DEBUG "!PLOT ON",CR                      'Start Plotting
DEBUG "!RSET",CR                         'Reset plot to time 0

' Define constants & variables

CS con 3                                ' 0831 chip select active low from BS2 (P3)
CLK con 4                                ' Clock pulse from BS2 (P4) to 0831
Dout con 5                               ' Serial data output from 0831 to BS2 (P5)
Datain var byte                           ' Variable to hold incoming number (0 to 255)
Temp var word                             ' Hold the converted value representing temp

TempSpan var word                         ' Full Scale input span in tenths of degrees
TempSpan = 5000                           ' Declare span 50 (1/100ths degrees)

Offset var word                           ' Minimum temp. Offset, ADC = 0
Offset = 700 ' Declare zero Temp. Set Vin(-) to .7 and
'Offset will be 700 tenths degrees. At these
'settings, ADC output will be 0 - 255 for temps
'of 700 to 1200 tenths of degrees.

Setpoint var word
Setpoint = 1015                           ' Initialize setpoint to 101.5 degrees

MMFlag var bit
MMFlag = 0

```

Experiment #5: Closed-Loop Control

```
LOW 8                                ' Initialize heater OFF

Main:
  GOSUB Getdata
  GOSUB Calc_Temp
  GOSUB Control
  GOSUB Display
GOTO Main

Getdata:                            'Acquire conversion from 0831
  LOW CS                            'Select the chip
  LOW CLK                           'Ready the clock line.
  PULSOUT CLK,10                     'Send a 10 uS clock pulse to the 0831
  SHIFTIN Dout, CLK, msbpost,[Datain\8] 'Shift in data
  High CS                            'Stop conversion
RETURN

Calc_Temp:                          'Convert digital value to
  Temp = TempSpan/255 * Datain/10 + Offset 'temp based on Span &
RETURN                              'Offset variables.

Control:                            'ON/OFF control
  IF Temp > Setpoint THEN OFF
  High 8                            'Heater ON
RETURN

OFF:                                'Heater OFF
  LOW 8
RETURN

Display:                            'Plot Temp and heater status
  IF OUT8 = 0 AND MMFlag = 0 THEN MMClear ' Clear Min/Max
  DEBUG DEC Temp,CR
  DEBUG IBIN OUT8,CR
RETURN

MMClear:                            'Clear Min/Max When setpoint is first reached.
  DEBUG "!CLMM",CR
  DEBUG "!USRS Overshoot/Undershoot Test Ready",CR
  MMFlag = 1
RETURN
```

Run the program and observe the behavior of the system. StampPlot Lite will graphically plot the temperature response of the system and the on-off status of Output 8. Follow the StampPlot Lite procedures of running the program, closing the debug window, opening StampPlot Lite, and pressing the “reset” button.

When you start your system, the heater will be on as indicated by the LED. The heater/resistor becomes quite hot when full power is applied. This heat transfers through the environment and warms the temperature sensor. When the sensor has heated to 101.5, the BASIC Stamp will turn off the heater. For a period after the heater is turned off, the temperature continues to rise. This is called overshoot. At this point, it is important to understand the dynamics of your system. The heat held within the mass of the resistor will continue to dissipate into the air, the air becomes warmer, and the LM34 reports that overshoot has occurred. Similar to the mechanical inertia of a moving object, this phenomenon is called thermal inertia. Overshoot becomes large when the heat energy contained in the mass of the resistor is large, relative to the heat already in the canister. The 35-mm canister is small, but the mass of the half-watt resistor also is small. As a result, the overshoot of your system will probably be less than one degree.

When the temperature does turn around and begin to fall, as it passes the setpoint, the heater is once again turned on. Undershoot will occur for similar reasons as did the overshoot. During the time the heater is coming up in temperature, the ambient temperature has continued downward. Continuous cycling above and below the desired setpoint is typical of on-off control. The rate of this cycling and the degree of the overshoot depend on the characteristics of the system. On-off control is suitable for processes that have large capacity, can tolerate sluggish response, and sustain a relatively constant level of disturbance. If our incubator were large, well insulated, and kept in a constant room environment, on-off control would be acceptable. After the process has had a chance to cycle a few times, record the minimum and maximum overshoot values.

Maximum overshoot _____ Minimum Overshoot _____

Using your cursor, investigate time between cycles. Record these times below.

Time at which the heater first turned OFF (T_{1off}): _____

Time at which the heater turned back ON (T_{1on}): _____

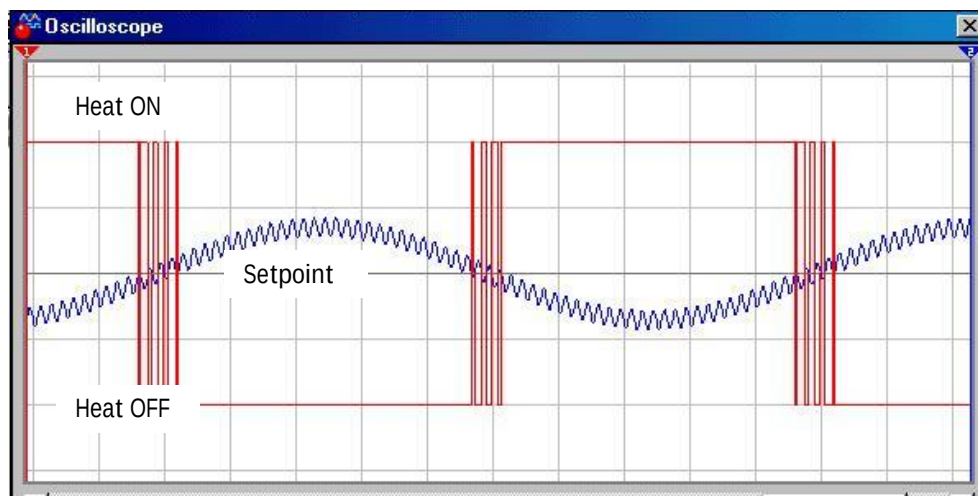
Time at which the heater turned OFF again (T_{2off}): _____

Cycle time = (T_{2off}) – (T_{1off}): _____

Experiment #5: Closed-Loop Control

A major problem with on-off control is that the output drive may cycle rapidly as the measurement hovers about the setpoint. Noise riding on the analog sensor measurement would be interpreted as rapid fluctuation above and below the setpoint. The timing diagram in Figure 5.3 represents this problem

Figure 5.3: On-Off Control When Noise Rides on the Data



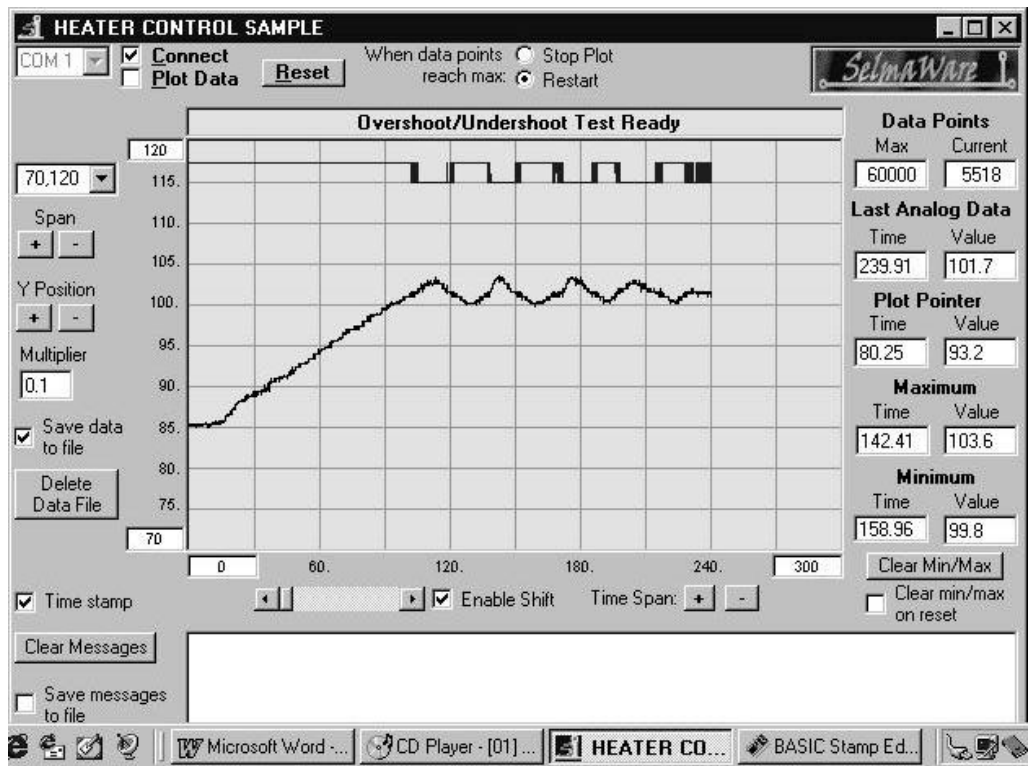
The slow-moving data that is cycling through the setpoint has a high-frequency noise component riding on it. As you can see, the coupled effects of the noise results in the data passing above and below the setpoint several times. The microcontroller would attempt to turn the heating element on and off accordingly.

In an actual incubator application where larger amounts of power are controlled, this rapid switching could cause unwanted RF noise. This rapid cycling could also be damaging to electromechanical output elements such as motors, relays, and solenoids.

Do you observe the rapid cycling of the LED as the temperature approaches the setpoint? _____

Remove the 22- μ F capacitor from across the sensor output. Does this increase the cycling problem? Why? Figure 5.4 is a typical screen shot resulting from this experiment. Overshoot and rapid cycling are a problem. Is this similar to your system's response?

Figure 5.4: Simple ON/OFF Control



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Experiment #5: Closed-Loop Control

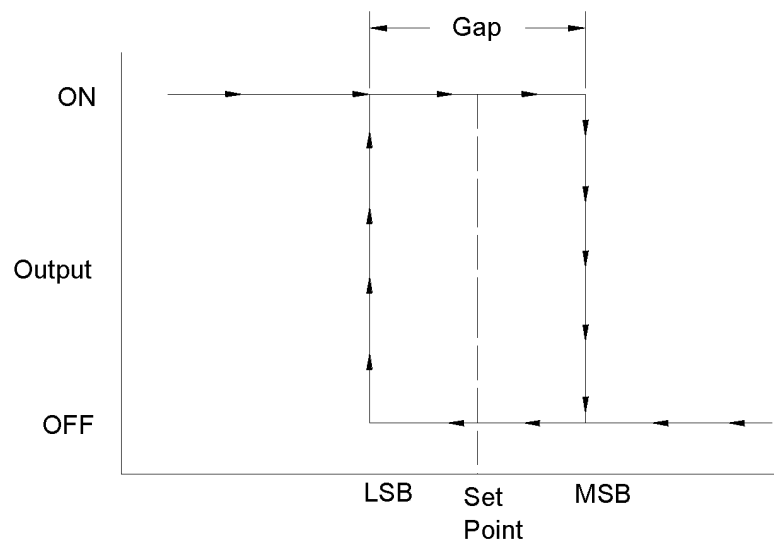
Challenge! Change the Dynamics of Your System

1. Connect your brushless fan to the Vcc supply and aim it toward the canister. Reset the program and watch the control action. Describe any effect that the new level of disturbance has on the overshoot and/or the cycling. Summarize how you have changed the dynamics of your system.
2. Place a single glass marble in your canister. Reset the program and watch the control action. Describe any effect that changing the mass of your system has on the overshoot and/or the cycling. Summarize how you have changed the dynamics of your system.

Exercise #2: Differential-Gap Control

The rapid cycling resulting from noise or the measurement hovering around a single setpoint is the biggest disadvantage of simple on-off control. Most practical on-off control systems lend themselves to allowing a minimum and maximum value of measurement. The incubator system is a good example. Although our desired temperature is 101.5 degrees, it allows ± 1 degree of variance about the setpoint. Differential-gap control is a mode of control that takes action based on the measurement crossing a defined upper and lower limit. When the measured value goes beyond one limit, full appropriate action is taken to drive the temperature to the opposite limit. Full opposite action is then taken to drive the process back again. Figure 5.5 graphically diagrams the action taken by differential-gap control. When the system is started and its temperature is below the Lower limit, the heater will come on and the temperature rise. When the temperature passes the upper limit, the heater is turned OFF, heat will begin to leave the process, and the temperature will begin to drop to below the Lower limit. The heat then is turned back on and the cycle begins again.

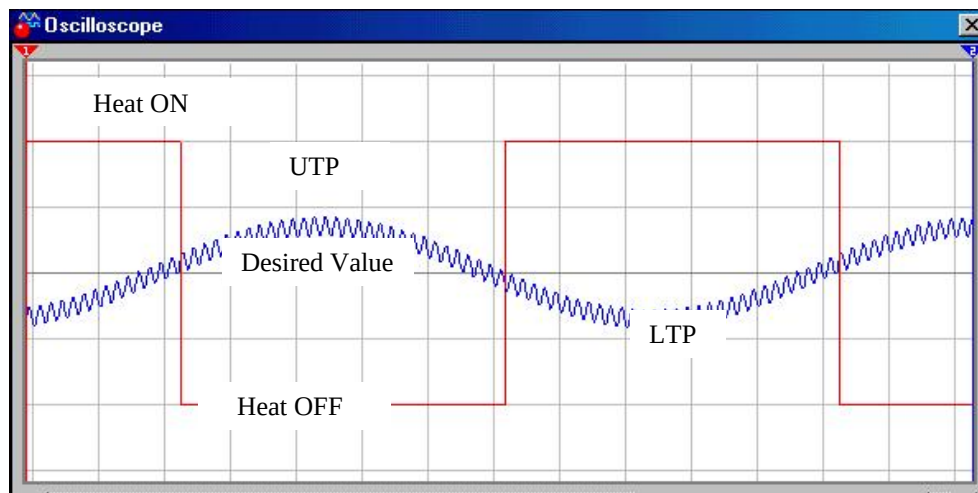
Figure 5.5: Differential-Gap Control Action

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The result is a slower on-off cycle time and no cycling resulting from noisy data. Notice how the timing diagram in Figure 5.6 differs from the earlier one depicting noisy data in a simple on-off control mode.

Whenever the measurement is anywhere between these limits, the heater state is not changed. The result is a slower ON/OFF cycle time and no cycling from noisy data. The heater is switched when the data (+noise) passes a limit. After that, the data (+noise) has to exceed the other limit before switching will occur again. Because the differential gap is wider than the effect of the noise, rapid cycling is eliminated.

Figure 5.6: Differential-Gap Control Action when Noise is Riding on the Data



These advantages come at the compromise of allowing the measured variable to drift further from the desired “average” value. The thermal inertia of our system will still result in some amount of overshoot and undershoot. We are accepting a wider variance in temperature. When processes allow this variance, differential-gap control is usually preferred over simple on-off control.

The **Control** subroutine can be easily changed to accommodate differential-gap control. Make the following modifications to Program 5.1.

Declare the new variables of **Upper_limit** and **Lower_limit** at the beginning of the program and initialize them to 102 °F and 101 °F respectively.

```
Upper_limit var word
Lower_limit var word
Upper_limit = 1020           ' 102 degrees in 1/10ths
Lower_limit = 1010           ' 101 degrees in 1/10ths
```

Next, replace the on-off **Control** subroutine with the following code.

```
Control:
  IF Temp > Upper_limit THEN OFF ' Over upper limit then Heat OFF
  IF Temp < Lower_limit THEN ON  ' Under lower limit then Heat ON
  RETURN                        ' return leaving heat in last state

OFF:
  Out8 = 0                      ' Heater Off
  maxflag = 1
  RETURN

ON:
  Out8 = 1                      ' Heater On
  RETURN
```

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Run the program and observe the behavior of your system.

Challenge! Observe and Evaluate Differential-Gap Control

Allow the program to cycle a few times. Report on the following:

Record the minimum and maximum overshoot temperatures.

Maximum overshoot _____ Minimum Overshoot _____

With your cursor, investigate time between cycles. Record these times below.

Time at which the heater first turned OFF (T_{1off}) _____

Time at which the heater turned back ON (T_{1on}) _____

Time at which the heater turned OFF again (T_{2off}) _____

Cycle time = (T_{2off}) - (T_{1on}) _____

Experiment #5: Closed-Loop Control

Project the switching point of the digital output down to the plotted temperature. Can you determine the temperature at which switching occurred? Momentarily remove the 22-uF filter capacitor. Does the increase in noise cause rapid cycling about the limits?

Use the fan to change the disturbances to the process. Reset the program and watch the control action. Describe any effect the new level of disturbance has on the overshoot and/or the cycling. Summarize how you have changed the dynamics of your system.

Place a single glass marble in the canister. Restart the program and summarize how increasing the mass has affected the process control action. Investigate the cycle time and overshoot.

Simple ON/OFF or Differential Gap?

Hopefully, the data that you have observed and recorded will reveal some important characteristics of these two control modes. They both have advantages and disadvantages. Simple on-off control results in rapid cycling of the heating element. Reported cycle times of less than one second could easily result if your system has fast recovery or there is noise on the analog line. Rapid cycle time would not be acceptable if our heater were being controlled by an electromechanical relay.

Notice, however, that the overshoot is approximately a half-degree and our average temperature is at the desired setpoint. Compare this control response to that observed when Differential Gap has been added to the On/OFF control.

With Differential-Gap control, you will notice fundamental differences in the control action.

1. Rapid cycling about the setpoint no longer occurs.
2. The minimum and maximum values still overshoot, but now beyond the limits.
3. Total cycle time between ON/OFF conditions is longer.

Increased cycle time and noise immunity about the setpoint are definite improvements over simple on-off control. The tradeoff, however, is allowing the process to vary further from the desired temperature setpoint. Obviously, an understanding of your process and its hardware will determine the appropriate control mode.

Both modes took appropriate control action to maintain temperature under changing disturbance levels and load conditions. The drawback to either mode of ON/OFF control is that the controlled variable is constantly on the move. The fully-ON and fully-OFF conditions of the final control element are continually forcing the measurement past the limits.

If you recall, in the Open-Loop Control exercise of Experiment #3, a value of drive between off and fully-on was found to be appropriate to hold the temperature at the setpoint. If all disturbances to the process remained constant, the temperature would stay at the setpoint when the right percentage of drive was applied. We also saw that as conditions changed, so did the measurement. Experiment #6 will investigate controls that take an appropriate amount of action based on an evaluation of the measurement. Applying Proportional, Integral, and Derivative control theory can be employed to maximize the effectiveness of the control system.



Programming Challenges

1. Alter your program so a ± 1 degree differential gap can be calculated automatically, based on the desired setpoint.
2. Add a variable called Differential_gap so the operator needs only to enter the Setpoint and the amount of Differential gap and the program automatically performs the desired action.



Questions

1. Write one complete sentence that clearly states the fundamental difference between Open-loop and Closed-loop controls.
2. Simple ON/OFF control compares the measurement of the process variable to a _____.
3. If the final control element to our model incubator were an air conditioner instead of a heater, what would change about Program 5.1?
4. When the process variable continues to increase after the final control element is turned OFF, it is termed _____.
5. Rapid cycling about the setpoint of an ON/OFF control system is a result of _____ riding on the measurement data.
6. List three devices that could not withstand rapid cycling of power.

7. Process cycle time is directly affected by the amount of _____ in the system.

8. Differential-gap control takes full action when the process variable crosses the _____ points.
9. Cycle time will be _____ if differential-gap control is used in a system rather than simple ON/OFF control.
10. Rapid cycling is not a problem in differential-gap control if the measurement data plus the _____ is less than the differential gap.
11. When the measurement is between the limits, the output will be in the mode determined by which limit was exceeded _____.
12. Adding more mass to a Differential-gap control system will _____ the amount of overshoot and _____ the cycle time of the process.

